Integration of Traffic Flow Management Decisions

Banavar Sridhar★ , Gano B. Chatterji[I], Shon Grabbe[*] and Kapil Sheth[+]

NASA Ames Research Center, Moffett Field, CA 94035

Abstract

The goal of traffic flow management in the national airspace system is to maintain efficient flow of air traffic without causing congestion and adversely impacting air traffic controller's workload. This paper describes a hierarchical method for integrating and improving traffic flow management actions in the current national airspace system. In the first step, traffic flow management actions like Playbook and coded departure routes are used for rerouting groups of aircraft flying in the same geographical neighborhood around flow-constrained areas. The rerouting process achieves the purpose of keeping traffic away from the flow-constrained areas, but in the process creates congestion and bottlenecks in other regions of the airspace. To prevent this congestion, an additional layer of control is imposed on this flow in the second step by temporal traffic decisions such as miles-in-trail, ground-stop and ground-delay program, which control the timing of the aircraft on fixed paths. This combination of rerouting with miles-in-trail, ground-stop and ground-delay program successfully prevents congestion at future time instants by controlling the departure times of aircraft on the ground. For aircraft that are airborne, the control choices are limited to miles-in-trail restrictions. The aircraft comply with the miles-in-trail restriction by altering their speed, or by introducing a delay via airborne hold or by stretching their flight path. An alternative approach is to reroute the aircraft through under-utilized neighboring regions. Following this approach, the third step of the hierarchical method locally reroutes few airborne aircraft around congested areas. The three-step hierarchical integration method is illustrated by an example that uses West North Brook (WNB) Playbook route along with miles-in-trail restriction at Fort Dodge Vortac and departure restriction at Minneapolis Saint Paul International (MSP) to reduce the demand on Sector 75 in Chicago Center (ZAU). Aircraft that are already airborne are locally rerouted around sector 75 to lower the traffic volume to within acceptable capacity limits.

★ Chief, Automation Concepts Research Branch; Mail Stop 210-10; E-mail: bsridhar@mail.arc.nasa.gov. Fellow, AIAA.

[I] Principal Scientist, Raytheon ITSS, Mail Stop 210-8. Associate Fellow, AIAA.

[*] Research Scientist, Automation Concepts Research Branch; Mail Stop 210-10. Member, AIAA.

[+] Principal Scientist, Raytheon ITSS, Mail Stop 210-8. Senior Member, AIAA.

Introduction

In the current national airspace system (NAS), a hierarchical process is used for traffic flow management (TFM). At the top level, air traffic control system command center (ATCSCC) uses computer-based forecasting tools such as the Enhanced Traffic Management System (ETMS) to forecast traffic over 3 to 24 hours time horizon [1]. Based on the expected weather conditions and demand in the sectors and airports, the ATCSCC specifies traffic management initiatives such as, Playbook routes (PRs), ground-stops (GSs) and ground-delay programs (GDPs). Local adjustments to these initiatives are proposed by the traffic management units (TMUs) in the air route traffic control centers (ARTCCs) at the next level. These initiatives are realized in terms of miles-in-trail (MIT) or minutes-in-trail (MINIT) restrictions. The traffic management problem derives its complexity due to the uncertainty in the information used for forecasting traffic and the inability to model the differing objectives and reactions of different decision makers to a dynamic situation. For example, the forecast does not take into account weather uncertainties, departure uncertainties, and airline response. Similarly, the ATCSCC is interested in overall flow, the TMU at the ARTCC is interested in the local flow and the airline operations center (AOC) is interested in schedule adherence. Even the traffic management initiatives such as Playbook routes, ground-stops, ground-delays and MIT are based on attempts at solving particular problems. For example, Playbook routes are used for circumventing severe weather, ground-stops and ground-delays are used for controlling demand at the airports, and MITs are employed for controlling workload in the sectors. The various TFM actions are imposed independently based on experience, and the interaction between these actions is not factored in making the decisions. The overall capacity of the NAS will be improved by developing methods to integrate and optimize the various traffic management initiatives such as-Playbook routes, GS, GDP and MIT to result in a single cohesive plan that improves traffic throughput, reduces delay, reduces congestion, and provides flexibility to the aircraft operators.

A three-step hierarchical method is developed in this paper with the objective of integrating TFM decisions. In the first step, Playbook and coded departure routes are used for rerouting groups of aircraft around flow-constrained areas. Regions of airspace impacted by weather, used for training or military operations, or congested due to large volume of traffic are classified as flow-constrained areas (FCAs). Since the rerouting process alters the usual flow of traffic, regions of congestion are created. Temporal flow controls such as miles-in-trail, ground-stop and ground-delay program are used in the second step to control the timing of the aircraft on fixed paths. The combination of spatial rerouting with temporal miles-in-trail, ground-stop and ground-delay program is useful in preventing bottlenecks at future time instants by controlling the departure times of aircraft on the ground. The suitable choices for the airborne aircraft are miles-in-trail restrictions or rerouting through under-utilized neighboring regions. The third step of the hierarchical method uses the latter choice of locally rerouting few airborne aircraft around congested areas.

The three-step hierarchical integration method was implemented in the Future ATM Concept Evaluation Tool (FACET), which provides a computational test-bed for evaluating air traffic management concepts. The steps of the algorithm are illustrated by an example that uses West North Brook (WNB) Playbook route along with miles-in-trail restriction at the Fort Dodge Vortac (FOD) and departure restriction at Minneapolis Saint Paul International (MSP) to prevent the capacity of sector 75 in Chicago Center (ZAU) from being exceeded. Aircraft that are already airborne are locally rerouted around sector 75 to lower the traffic volume to within acceptable capacity limits.

The rest of the paper is organized as follows. Section 2 describes FACET. Section 3 describes the routing process using Playbook routes. This section also discusses the use of temporal controls such as MIT and GDP to control traffic congestion resulting from the routing process. The last step of the hierarchical technique, which uses local rerouting, is presented in Section 4. Results discussed in Section 5 show that the integrated technique is able to keep aircraft out of the FCAs without overloading sectors. Finally, the paper is concluded in Section 6.

Modeling Using FACET

Future ATM Concepts Evaluation Tool (FACET) is an air traffic management decision support tool being developed at the NASA Ames Research Center. FACET provides an environment for developing and evaluating traffic flow management initiatives before they are operationally deployed by modeling system-wide airspace operations over the United States [2]. FACET can be broadly described in terms of three subsystems: 1) database, 2) algorithms and 3) graphical user interface (GUI) as follows.

The geometry database in FACET contains the structure of the airspace over the United States in terms of regions controlled by the 20 air route traffic control centers (ARTCCs). The horizontal boundaries of the ARTCCs and the horizontal and vertical boundaries of all low-altitude, high-altitude and super-high-altitude sectors within each ARTCC are included in the database. Victor airways and jet routes are represented in terms of the fixes (navigation aids and airway intersections) that define them. Position data for each fix is available within the database. The database also contains locations of over thirteen thousand U.S. airports.

The aircraft performance database in FACET contains performance models for 60 different aircraft types. It also contains an equivalence list that maps the 500+ aircraft types recognized by the Federal Aviation Administration (FAA) to these 60 performance models. The performance model for an aircraft is provided as airspeed and altitude-rate tables, derived from the calibrated airspeed (CAS) and Mach schedules, as a function of altitude during the climb and descent phases of flight. For cruise phase (zero altitude-rate), the airspeed is tabulated as a function of cruise altitudes for the particular aircraft type.

The flight database is continually updated based on the schedule, flight plan and track data provided by the ETMS. The schedule data consist of the flight identification, estimated time of departure and actual departure time if the flight has already departed. The flight plan data include aircraft identification, type of aircraft and the route of flight. The track data consist of the aircraft identification and the position of aircraft specified in terms of latitude, longitude and altitude. Aircraft identification tag allows the schedule, flight plan and track data to be tied to the same aircraft within the database. As aircraft land, they are removed from the database.

The algorithms that ingest data from the databases and provide the decision support data to be displayed on the GUI form the central core of FACET. Route parsing and trajectory prediction algorithms are the important ones in this category. The route-parsing algorithm converts the flight plan provided by the flight database into a sequence of waypoints specified in terms of latitude-longitude pairs. The flight plan route is available from the flight database in terms of the names of fixes, fix radial distance (FRD) and coordinates of points along the route. The route parser uses the fix name to access position data from the geometry database. It is able to convert the FRD into a position because FRD is specified in terms of distance and bearing with respect to a named fix, whose position it knows via the geometry database.

FACET models 4D aircraft trajectories using round-earth kinematic equations. The trajectory prediction algorithm forecasts the future position of the aircraft along the planned route by propagating the equations of motion forward in time driven by the heading, airspeed and altitude-rate dynamics. These dynamics are a function of the climb, cruise and descend data obtained from the aircraft performance database. Initial conditions such as, the scheduled time of departure and track position for trajectory prediction are obtained from the flight database. For a detailed description of the trajectory modeling process, see Reference 2. Trajectory modeling capability provides FACET with the ability to forecast traffic in the sectors, fixes and airports being monitored, which makes decision support possible. Constraints such as reroutes, MIT at fixes and GDP at airports can be included in the trajectory prediction process to evaluate the impact of flow management initiatives.

The control and display of all information in FACET is achieved through a menu-driven GUI. FACET utilizes oblique stereographic projection for displaying airspace features and air traffic on the GUI. Figure 1 shows the boundaries of the ARTCCs, high-altitude sectors and the traffic.

Algorithms in FACET are implemented using the C programming language and GUI using the Java programming language. The dual programming language architecture has resulted in efficient computation and platform independence.

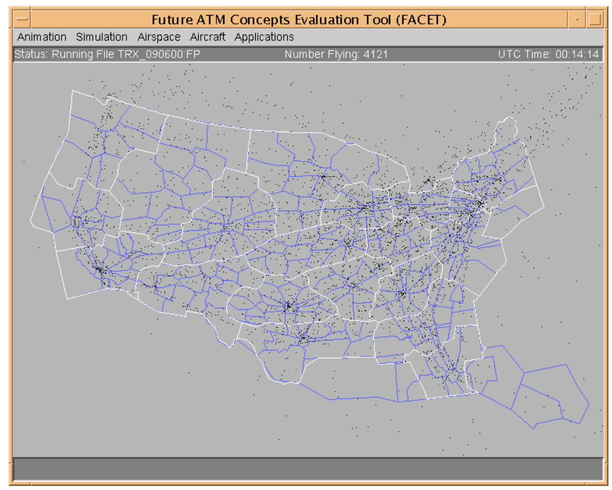


Figure 1. FACET display of traffic.

Rerouting Using Playbook Routes

The first step of the method consists of selecting routes from the National Playbook for rerouting aircraft around regions of severe weather. The rerouting process alters the usual flows of traffic and causes congestion in sectors through which traffic is diverted. Temporal restrictions such as MIT and GDP are then used by the method to prevent such congestion.

The National Playbook is a compendium of alternative routes for avoiding specific regions of airspace that are known to be impacted by severe weather during certain times of the year, based on historically validated data. Playbook also contains alternative routes for circumventing closed segments of airways, non-operational navaids, and airports that are impacted by weather or runway closures [3]. One of the planning templates, known as West North Brook, is provided in Playbook for rerouting traffic through the Denver, Chicago and Minneapolis ARTCCs when a FCA blocks a large portion of airspace in the Midwest.
Figure 2 shows the West North Brook routes for the transcontinental traffic on the FACET display. The

large rectangular region west of Chicago in this figure marks a potential severe weather region. Any flight that is scheduled to pass through this region is rerouted away using the West North Brook routes. For example, the Playbook route is used for rerouting the flight COA160 from John Wayne airport (SNA) to Newark airport (EWR) with the planned route: SNA.MUSEL6. TRM.J236.TBC.J128.HBU.J146.GLD. J192.PWE.J64. BDF.J26.JOT.J146.GIJ.J554.CRL.J584.SLT.FQM1.EWR, that passes straight through the severe weather region as shown in Figure 3. The resulting route is specified as: SNA./.BCE.J100.EKR. BFF.J94.OBK. J584.FQM.FQM1.EWR. Observe from Figure 3 that this new route avoids the severe weather region entirely. Note that the routes are specified in terms of navaids such as BCE, jet routes such as J100, and standard terminal arrival routes such as FQM1. The ./. notation indicates that there are intermediate navaids on the route between the SNA and BCE navaids.

Visual examination of the West North Brook routes in Figure 2 shows that flows from Dubois (DBS), Sacramento (SAC) and Bryce Canyon (BCE) can merge into single flows over some segments of the route structure, which can cause bottlenecks due to traffic volume. Traffic counts, obtained with West North Brook, that are described in the Results Section, show that this indeed is the case. It is easy to see from Figure 2 that the first step of the hierarchical method achieves the basic purpose of keeping traffic out of chosen regions, but in the process can cause congestion and bottlenecks in other regions of the airspace.

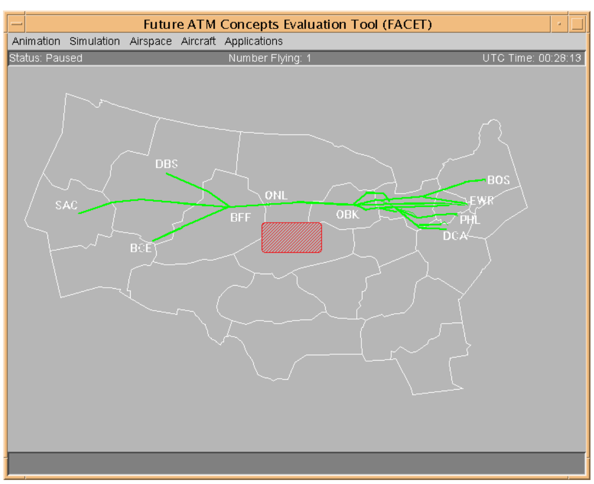


Figure 2. West North Brook routes on FACET display.

In the current air traffic management system, historically validated MIT and GDP restrictions are routinely used to mitigate congestion; therefore, it is only reasonable to use MIT and GDP as the second step of the technique. A traffic scenario is used for describing the effects of using the West North Brook route along with MIT and GDP controls to keep the traffic volume within acceptable limits in the Results Section.

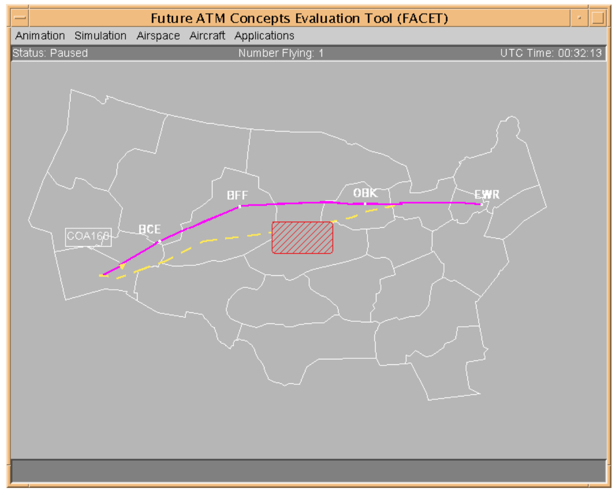


Figure 3. Nominal and Playbook route for COA160.

Local Rerouting For Congestion Control

The two steps of the hierarchical method of applying the Playbook routes for avoiding flow constrained areas and controlling congestion via MIT and GDP techniques are suitable for flow control at future time instants if a significant fraction of the traffic is presently on the ground. For airborne traffic, only MIT and further rerouting can be used for preventing congestion. Since MIT is applied to the entire stream of aircraft, it lacks the flexibility that is needed for minor adjustments. A local rerouting procedure that allows a few aircraft to circumvent the congested areas is much more suitable because it builds on the previous solution and prevents a more severe application of the MIT restriction.

This section describes an algorithm that is implemented in FACET for rerouting aircraft locally around flow-constrained areas. A flow-constrained area in this context is defined to be a sector whose capacity is exceeded. Sector capacity is defined in terms of the peak traffic through the sector in a fifteen minutes time interval [1]. FACET is used for forecasting traffic counts in the sectors using the Playbook routes and the MIT and GDP restrictions. Sectors whose capacity is predicted to be exceeded are identified as flow-constrained areas. All aircraft whose planned routes pass through these regions are flagged as candidates for local rerouting. The algorithm then selects the minimum number of aircraft, based on their distance from the impacted sector, that need to be rerouted for preventing sector overload.

The algorithm is designed to minimize the number of inflection points in the rerouted trajectory that avoids the FCA. For the polygon that defines the FCA, there are an infinite number of routes that can be constructed on either side of the polygon partitioned by the straight-line connecting the origin to the destination, shown in Figure 4. This fact makes it possible to use alternative routes that prevent sector capacity thresholds from being exceeded. For example, if the sector on one side of the FCA is capacity limited, the route from the opposite side can be used. The other feature of this rerouting algorithm is that as sector capacities are reached, the FCA is grown to include the impacted sectors and routes are constructed to circumvent these larger FCAs.

The algorithmic details of the rerouting method are as follows. As an example, consider the FCA shown in Figure 4. Its vertices P1 through P8 define the outer boundary of the polygon. The origin of the rerouting segment is Po and the destination is Pf. As the first step, the intersections of the straight-line joining the origin, Po, to the destination, Pf, with the line segments connecting the vertices of the polygon are determined. Observe in Figure 4 that the intersection points are Q1 and Q2, which are obtained via intersection with P1-P8 and P5-P6 edge-segments. The closest and the farthest intersection points with respect to the origin point are found. In this example, Q1 is the closest intersection point and Q2 is the farthest intersection point with respect to the origin Po. The midpoint point between these two extreme points is found, which in this case is Qm. Distances from the midpoint to the vertices on the two sides of the polygon about the origin-destination axis are obtained. The vertices on the upper side are P1 through P5 and the ones on the lower side are P6 through P8. The smaller of the largest distances on the top and bottom sides is chosen as the radial distance for drawing an arc centered about the midpoint. For the example in Figure 4, the radial distance is Lr, which is the distance between Qm and P6. Next, a normal to the straight-line connecting the origin to the destination, Po-Pf, or Q1-Q2, is constructed from the midpoint, Qm, in the direction of selected side. The intersection point of the arc and the normal, Ra, is found. The reroute path is determined as segments connecting the origin to the destination via the inflection point, Ra. If the path from the origin to the inflection point is found to intersect the FCA, the route construction procedure is repeated with the inflection point as the intermediate destination point. Once a new inflection point is evaluated, it is treated as the new point of origin. The algorithm proceeds with the new origin and final destination. The complete route is obtained recursively, in the forward and backward direction, until a clear route from the true origin, Po, to the final destination, Pf, is found. This route synthesis procedure results in routes that have minimum number of inflection points. For the example shown, there is a single point of inflection.

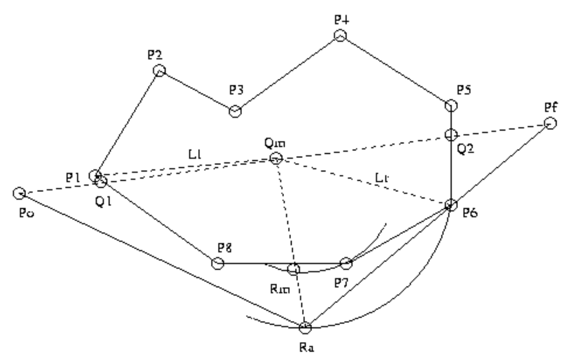


Figure 4. Local rerouting around an FCA.

If routes that closely follow the boundary of the FCA are desired, the smallest arc length from the midpoint, Qm, to a vertex on the same side of the polygon, where the smaller of the two largest distances to the vertices on the opposite sides was found, can be used. For the example in Figure 4, this is the side containing the vertex P6. Let the radius of the arc be the distance between the midpoint Qm and the vertex P7, and the intersection point of the arc with the normal be Rm. With Rm as the inflection point, the algorithm can be used for constructing the path as described earlier.

Figure 5 shows the route creation process in which the chosen sector (Sector 75 in Chicago ARTCC) is avoided to prevent the capacities of this sector and the neighboring sectors from being exceeded. A portion of the nominal route of the aircraft DAL2208 from Salt Lake City (SLC) to Detroit (DTW) is shown in Figure 5. This portion of the route is marked in white. The rerouted path taken by the aircraft while it is in the Minneapolis ARTCC airspace is shown in black.

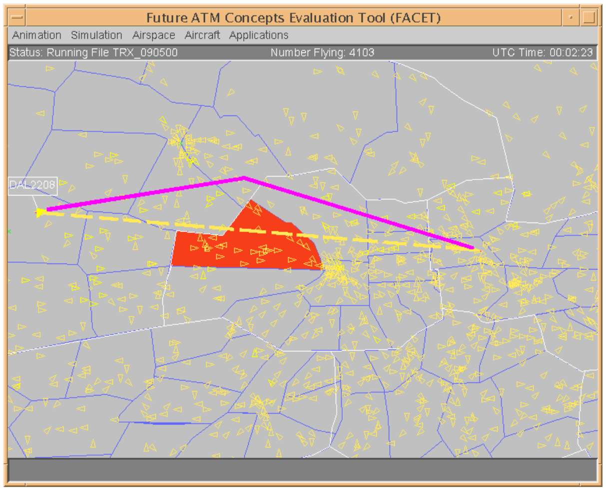
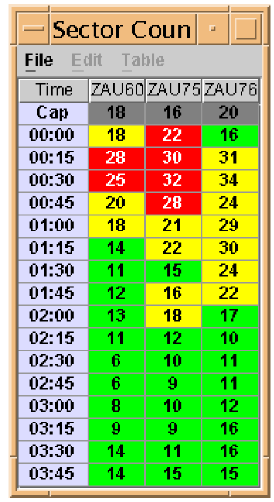


Figure 5. DAL2208 is routed around the congested Sector 75 in the Chicago ARTCC.

Results

To evaluate the potential of integrating the various traffic management initiatives using the three-step hierarchical method, proposed in this paper, real air traffic data for a 24-hour period were collected using the ETMS system. The data were recorded on September 5th, 2000. The origin, destination and the flight plans (including amendments) of the individual flights were used along with the other data (aircraft performance and airspace structure) in FACET to forecast the traffic. The traffic data were then used for computing the peak traffic through the sectors in fifteen minutes time intervals. Figure 6 shows the peak traffic through Sectors 60, 75 and 76 of the Chicago ARTCC (ZAU) in fifteen minutes time buckets for the nominal scenario, without rerouting and metering restrictions. FACET presents the data in the form shown in Figure 6.

The peak counts obtained for the nominal traffic condition are presented together with those obtained with rerouting and metering in Table 1. The first column of Table 1 shows the time intervals and the second column shows the peak traffic counts through Sector 75 of the Chicago ARTCC. The capacity value (also known as the monitor alert parameter- MAP) for this sector is 16 aircraft. The positive numbers indicate that the capacity will be exceeded while the negative numbers indicate that the demand is below the sector capacity. Letter *A* is added to the counts to indicate that the airborne aircraft alone will exceed the capacity, although a combination of airborne and possibly those on the ground exceed it. The letter *G* indicates that the capacity will be exceeded by a combination of airborne aircraft and those currently on the ground, but not by the airborne aircraft alone. GDP procedures can be used in both these situations to change the future demand by aircraft that are presently on the ground. For example, if the six aircraft predicted to be in the fifth time bin are ground delayed in the nominal scenario (see: the value in the second column corresponding to the 01:15 time bin), the capacity of Sector 75 would not be exceeded.



Time	ZAU60	ZAU75	ZAU76
Cap	18	16	20
00:00	18	22	16
00:15	28	30	31
00:30	25	32	34
00:45	20	28	24
01:00	18	21	29
01:15	14	22	30
01:30	11	15	24
01:45	12	16	22
02:00	13	18	17
02:15	11	12	10
02:30	6	10	11
02:45	6	9	11
03:00	8	10	12
03:15	9	9	16
03:30	14	11	16
03:45	14	15	15

Figure 6. FACET display of peak traffic counts in Sectors 60, 75 and 76 of the Chicago ARTCC.

Time	Nominal	WNB Rerouting	WNB+MIT +GDP
00:15	+30 A	+35 A	+26 A
00:30	+32 A	+37 A	+27 A
00:45	+28 A	+33 A	+25 A
01:00	+21 G	+26 G	+18 G
01:15	+22 G	+26 G	+22 G
01:30	-15	+17 G	-15
01:45	16	+19 G	+18 G
02:00	+18 G	+22 G	+20 G
02:15	-12	+17 G	16
02:30	-10	16	-12
02:45	-9	-14	-10
03:00	-10	+17 G	-13
03:15	-9	+18 G	-12
03:30	-11	+21 G	-13
03:45	-15	+26 G	-13

Table 1. Peak traffic counts – hierarchical method.

Ground delaying all the aircraft that are predicted to be in the first time bin (00:15) for the nominal scenario (+30 A) would not bring the demand below the sector capacity because the airborne aircraft alone would cause the capacity to be exceeded.

The impact of rerouting traffic using West North Brook (WNB) is summarized in the third column of Table 1. Observe by comparing the third column to the second column of the table that the rerouting causes the capacity to be exceeded at several additional time instants and that the increase is larger. The sector overload is brought down significantly by applying a 50 MIT restriction at Fort Dodge Vortac and an airport departure rate constraint of ten aircraft per hour at the Minneapolis Saint Paul International. The fourth column of the table summarizes the results with the restrictions. The results in the table are shown as time histories in Figure 7. This figure shows that the restrictions are able to reduce the sector demand caused by the use of the West North Brook route by half. Figure 7 also shows that beyond 2.25 hours, the sector capacity utilization is improved by using the West North Brook route and the restrictions (WNB+MIT+ GDP) since the peak count is closer to the capacity threshold value of 16 aircraft.

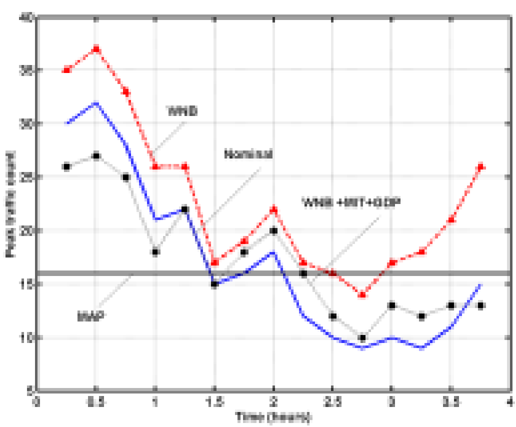


Figure 7. Peak traffic counts in Sector 75 of the Chicago ARTCC.

Although the MIT and departure restrictions are helpful in reducing congestion in Sector 75 of the Chicago ARTCC, they are not completely successful in bringing down the demand below the capacity threshold. Thus, individual aircraft, which are not airborne currently but are predicted to be responsible for congestion at future time instants, will be subject to departure delays. This would eliminate the excess demand by these aircraft. The remaining few airborne aircraft will be rerouted around Sector 75 using the local rerouting algorithm described earlier in Section 4. This completes the third and the final step of the hierarchical method described in this paper.

Conclusions

A three-step hierarchical method was presented to integrate the traffic flow management initiatives for avoiding regions of severe weather and preventing congestion in the sectors. The method consists of using Playbook routes for avoiding severe weather regions and then using a combination of miles-in-trail, ground-delay and local rerouting to control demand in the sectors. To evaluate the potential of this method, a realistic traffic simulation driven by actual air traffic data was used with the West North Brook route structure from the National Playbook to circumvent a region of severe weather located to the West of Chicago. It was shown that the traffic following West North Brook caused the capacity of Sector 75 of the Chicago Center to be exceeded. Miles-in-trail and departure restrictions were used for lowering the traffic volume. The excess airborne traffic was then rerouted around Sector 75 using the local rerouting algorithm described in the paper. The results obtained for this scenario demonstrates that the hierarchical method is able to reduce the demand to be within the capacity thresholds of the congested regions of the airspace.

References

1. "Enhanced Traffic Management System (ETMS)," Report No. VNTSC-DTS56-TMS-002, Volpe National Transportation Center, U. S. Dept. of Transportation, Cambridge, MA, March 31, 1999.

2. Bilimoria, K., Sridhar, B., Chatterji, G. B., Sheth, K., and Grabbe, S., "FACET: Future ATM Concepts Evaluation Tool,'' Air Traffic Control Quarterly, Vol. 9, No. 1, 2001, pp. 1-20.

3. Air Traffic Control System Command Center, "National Severe Weather Playbook," http://www.fly.faa.gov/Operations/Strategic_Planning/playbook_html/index.htm, November 1, 2001.